Scientific Review Engineering and Environmental Sciences (2024), 33 (2), 115–130

Sci. Rev. Eng. Env. Sci. (2024), 33 (2) https://srees.sggw.edu.pl

ISSN 1732-9353 (suspended) eISSN 2543-7496 DOI 10.22630/srees.9790

Received: 03.05.2024
Accepted: 16.05.2024

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From a test case to a trusted tool: Lithuania's evolving SWAT system for water and agricultural management

Keywords: modelling system, model management, water management, institution, decision support

Introduction

Agricultural activities are among the major sources of greenhouse gases (Chataut et al., 2023), biodiversity loss (Tsiafouli et al., 2015) and water pollution around the globe (Food and Agriculture Organization of the United Nations [FAO], 2017). According to the studies, agriculture is the leading culprit behind river and lake pollution in the United States (Evans et al., 2019), China (FAO, 2013), where it is estimated to render a staggering 90% of shallow groundwater unfit for human consumption (Lu & Villa, 2022), and the EU (European Environmental Agency [EEA], 2018) severely affecting around 38% of EU water bodies. As expected, population growth, rising per capita food consumption (FAO, 2017) and changing climate is putting even more pressure on water ecosystems (Heathwaite, 2010).

The need to protect and restore water bodies from deterioration has been recognized for nearly half-century in the USA with a major amendment of the Federal Water Pollution Control Act in 1972, to be shortened as Clean Water Act (Laitos

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& Ruckriegle, 2012). In the EU, the same has been done with major water protection legislations such as the Nitrate Directive (Directive 91/676/EEC) and the Water Framework Directive – WFD (Directive 2000/60/EC). Intergovernmental bodies such as the Helsinki Commission (HELCOM, 2023a), bridging the gap between scientific research and policy to safeguard specific water bodies, were established in 1974 (HELCOM, 2023b). These instruments set out standards for the quality of water in the environment and the maximum levels of pollution allowed, aiming to safeguard or improve the condition of water bodies to a "good" state.

However, achieving these objectives has proven to be challenging, especially difficult is addressing diffuse pollution coming from agriculture (EEA, 2020). Recent studies indicate that despite extensive efforts to implement the WFD and other water regulations, nutrient loads from agriculture, especially nitrogen, are on the rise (Nõges et al., 2022; Vigiak et al., 2023). Implementing agricultural pollution control measures have been largely ineffective due to poorly designed policies, lack of targeted approaches, low prioritization, and insufficient integration with farming practices (Brady et al., 2021; Thorsøe et al., 2021). Furthermore, water policy and management design lacks consideration of cost-effectiveness and fails to simultaneously address multiple objectives, such as reducing water pollution, mitigating greenhouse gas emissions, protecting soils, and enhancing agricultural resilience to droughts (Andersson et al., 2022). Addressing such issues requires the utilization of advanced modelling techniques.

The soil and water assessment tool (SWAT) model is one example, which is a powerful tool used worldwide to assess hydrology, water quality, soil health, agricultural or climate impacts (Gassman et al., 2014; Gassman & Yingkuan, 2015; Tan et al., 2019, 2020). Over 6,500 scientific articles document its capabilities in the SWAT Literature Database (Center for Agricultural and Rural Development and Iowa State University, 2023), with the history of development spanning over several decades (Arnold et al., 1998). However, the benefits of using the SWAT model extend far beyond academia. For example, the United States demonstrated its successful application for calculating total maximum daily loads (Borah et al., 2006), evaluating conservation programs (White et al., 2014) or environmental decision-making (White et al., 2022).

Yet, documented examples of the SWAT use in water management institutions in scientific literature outside the US are scarce. There are plentiful sources evaluating the SWAT model's suitability for solving questions related with implementation of the WFD (Bärlund et al., 2007; Kronvang et al., 2009), objectives of the Helsinki convention (Nasr et al., 2007; Piniewski et al., 2020) or even society's development paths (Carstensen et al., 2023), however, only a few articles were available describing the model development within institutions. For instance, one study for Uruguay (Mer et al., 2020) described a multi-agency effort to build a SWAT model application within a participatory modelling project. Another study (Arnold et al., 2020) introduced the conceptual framework of modelling and model management issues associated with using and developing models within catchment management agencies. In this paper, the authors present cases and lessons learnt from managing catchment models in national or regional institutions in Denmark, the UK, the Netherlands and Canada. Another work (Fu et al., 2020) examined the challenges and actions needed to support and improve water quality modelling within organizations. The study by Vervoort et al. (2024) provided an overview of the integration between science and policy development facilitated by integrated watershed models. However, we have not been able to find a specific example that describes the case of an advanced water modelling tool being developed and used for many years by a single water management institution. This article aims to remedy this situation by providing an insight into the case of Lithuania, where the main water management institution has been using a SWAT-based water modelling system for more than a decade.

Material and methods

In the preparatory phase for EU compliance (i.e. before 2004), it became evident to the Lithuanian Environmental Protection Agency (EPA) and the Ministry of Environment that advanced water modelling tools were essential to address the environmental management and data reporting inquiries mandated by EU regulations. Several trials have been conducted initially with different tools. In 2003, the Danish Hydraulic Institute (DHI) proposed to conduct a comprehensive study to identify optimal modelling options for EPA (Lawson, 2021). This study was completed in 2004 and recommended the use of the MIKE BASIN model (no longer available as of 2014, replaced by MIKE HYDRO Basin) developed and sold by the DHI. MIKE BASIN, an empirical, lumped parameter, continuous time scale, river basin model designed primarily for water allocation issues, has additional capabilities for assessing nutrient loads from multiple sources (Danish Hydraulic Institute Water & Environment, 2003). This model was employed in the initial phase of preparing river basin management plans (RBMPs) across Lithuania, culminating in 2010. However, significant constraints were encountered during the RBMPs preparation projects. For example, the water quality component of the model could only generate information on total watershed loads based on statistical data, and its coefficients have no physical meaning, making predictions highly questionable. In addition, this

Plunge, S., Piniewski, M. (2024). From a test case to a trusted tool: Lithuania's evolving SWAT system for water and agricultural management. *Sci. Rev. Eng. Env. Sci.*, *33* (2), 115–130. DOI 10.22630/srees.9790

model does not take into account crucial factors influencing diffuse pollution, such as land use, soil characteristics and slope, indicating unreliable results for, among others, modelling non-point source pollution generated by agriculture, which constitutes the main cause of water ecosystem degradation in the country (Aplinkos apsaugos agentūra [AAA], 2009). These limitations implied the need to change the model selection and the modelling approach. Several criteria (Saloranta et al., 2003) were identified in this process:

– Ability to evaluate non-point source pollution in inland water bodies and the environmental effect of implementing mitigation strategies;
– Adaptable for answering WFD questions;
– Compatibility with existing data sources;
– Seamless integration with geographic information systems (GIS);
– Low costs;
– Comprehensive documentation;
– Documented history of successful model applications and extensive development timeline;
– Strong technical support system.

The SWAT model checked all the required boxes and was selected as a tool to be examined with a national test case. The small catchment (14.2 km^2) of the Graisupis river was chosen as a pilot area. Situated in the center of Lithuania, this catchment is predominantly agricultural, covering over 71% of its area. It was selected due to the presence of a long-term monitoring program dedicated to assessing agricultural pollution within the region. Consequently, an abundance of valuable data pertaining to water quality and agricultural practices was readily accessible for analysis. The model application in the Graisupis river catchment was successfully demonstrated for different water management purposes (Plunge, 2009, 2011). This allowed the EPA to proceed with the preparation of the modelling system covering all of Lithuania, as well as areas outside the country that generate flows into Lithuania (Fig. 1).

The development of the national model involved three iterations within three consecutive projects. The first one started in 2011 and was completed in 2012 (Procesu analīzes un izpētes centrs [PAIC] & Estonian, Latvian & Lithuanian Environment, 2012). The second one was completed in 2015 (PAIC, 2015), and the third one in 2022 (PAIC, 2022). During the first iteration, the national model was created and tested with available data. The aim of the second project was to build a modelling system fully based on the Python script library. Additionally, the model was extended to cover the entire Nemunas basin (e.g. areas in Belarus and Poland draining into Lithuania). The third project was designed to migrate the existing system from SWAT2012 to the SWAT+ model, re-calibrating, updating input data, upgrad-

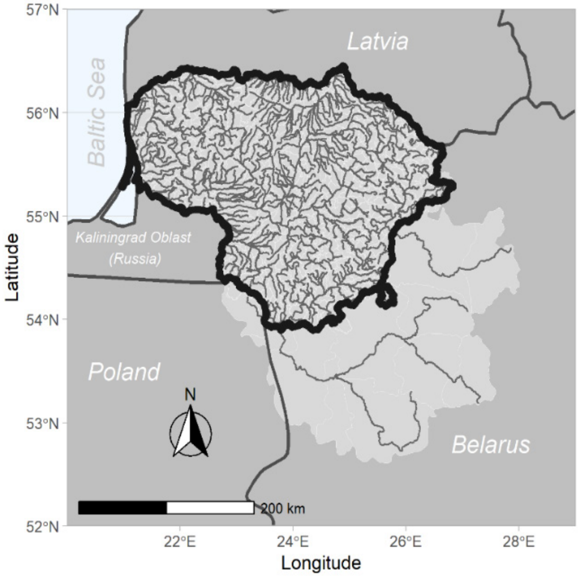

FIGURE 1. Area covered by the model (bold line marks territory of Lithuania, light gray – area covered by the model, thin gray lines – water bodies represented in the model)

Source: Plunge et al. (2022b).

ing the system to model small river water bodies and the modelled network to align with WFD water bodies, upgrading the script library to include automatic building of scenarios for measures, extraction of results and adding new data sources such as rainfall radar (PAIC, 2022). SWAT+ is a new model version characterized by a comprehensive restructuring of inputs and code (Bieger et al., 2017), integrating novel concepts, such as enhanced flexibility in water routing across landscapes (Bieger et al., 2019), decision table (Arnold et al., 2018), etc. Additionally, all the modelling systems were fully transferred to the open source tools using Python (Python Software Foundation, 2023) as the main scripting language, PostgreSQL (The PostgreSQL Global Development Group, 2024) – for database related tasks, PostGIS (PostGIS PSC & OSGeo, 2024) – GIS-related and R (R Foundation, 2024) for some *ad-hoc* input, output data processing tasks.

The constructed system was called the river modelling system (RMS). It has options to be run in two resolution levels (PAIC, 2022). The coarse level, separating the country into 1,335 catchments (individual size does not exceed 80 km^2), corresponds to water bodies defined for the WFD purposes. The detailed level separates the model into 11,490 catchments corresponding to the river, lake and reservoir cadaster data (AAA, 2024). The most detailed recent national and international datasets were processed and integrated as SWAT model inputs. Data were provided by multiple institutions as well as experts in specific fields (agriculture, soil, etc.). The main data sources used in the RMS preparation included (Plunge et al., 2022b):

– GIS data of the Rivers, Lakes and Ponds Cadastre of the Republic of Lithuania (EPA) [scale 1:10 000];
– Digital terrain map generated from land surface laser scanning point – SEŽP_0,5LT data (National Land Service) [two-meter spatial resolution];
– Soil data from a soil database – DIRV_DR10LT (National Land Service) [scale 1:10 000];
– Forest Cadastre data (Forest Service) [scale 1:10 000];
– Declared crops data (Agriculture Information and Rural Business Center) [scale 1:1000];
– Abandoned land data – AZ_DR10LT (National Land Service) [scale 1:10 000];
– National geospatial data – GDR10LT (National Land Service) [scale 1:10 000];
– The high-resolution Imperviousness Layer (Geoland2) [10-meter spatial resolution];
– Quaternary geology data (Lithuanian Geological Survey) [scale 1:200 000];
– Soil properties' table (soil expert) [parameter values for the profiles of different soil types existing in DIRV_DR10LT and Forest Cadastre data];
– Meteorological data (Hydrometeorological Service) [mean daily and hourly measurements];
– Point source pollution data (EPA) [yearly means and monthly for big sources (monthly only available for periods of 2006–2016)];
– Water quality monitoring (EPA) [monthly values];
– Water flow data (Hydrometeorological service) [daily flow means];
– Agricultural statistics (Department of Statistics) [yearly statistical data];
– Water extraction (EPA) [yearly data];
– Crop fertilization data (agricultural expert) [amounts for different crops, application methods and timing];
– Belarus data [scale 1:500 000] (Holmlund & Hannerz, 2007);
– EU-DEM v1.17 from Copernicus Land Monitoring Service [30-meter spatial resolution];
– Bathymetry of water bodies (EPA) [one-meter spatial resolution];
– Groundwater pollution (EPA) [modelled mean concentrations];
– Tile drain data – MELDR10LT (National Land Service) [scale 1:10 000];
– Reservoir storage capacity (EPA) [fixed values from reservoir operation rules];
– Atmospheric deposition (European Monitoring and Evaluation Program) [0.1-degree grid].

Results and discussion

The main result of these multi-year efforts is the developed river basin modelling capacity within the EPA. This capacity is now being applied (or in the process to be applied) to address various water management questions. The EPA takes charge of these questions, which encompass tasks arising from the WFD, the Baltic Sea Action Plan (BSAP) for implementing the Helsinki Convention, the Nitrates Directive, the Common Agricultural Policy (CAP), the Environmental Impact Assessment Directive (Directive 2011/92/EU), the Climate Change Convention (greenhouse gas reporting), the Flood Directive (Directive 2007/60/EC), the Marine Strategy Directive (Directive 2008/56/EC), and various reporting requirements for both the European Environment Protection Agency (EEA) and national reporting needs.

The RMS has been calibrated, validated and tested during the preparation of the river basin management plans. Statistical performance evaluation is presented in Figure 2. Soft calibration was utilized to ensure that hydrology and nutrient processes conformed to the available data, including yields and subsurface flow. The model was calibrated/validated using a total of about 62 hydrological stations and 130 stations for water quality data. However, extensive calibration/validation was carried out on representative stations representing 14 regions according to hydrological and pollution generating conditions (Plunge et al., 2022b). Results show that the RMS performs well compared to the observation data. Similar performance levels were kept while transitioning from SWAT2012 (PAIC, 2015) to SWAT+ models (PAIC, 2022).

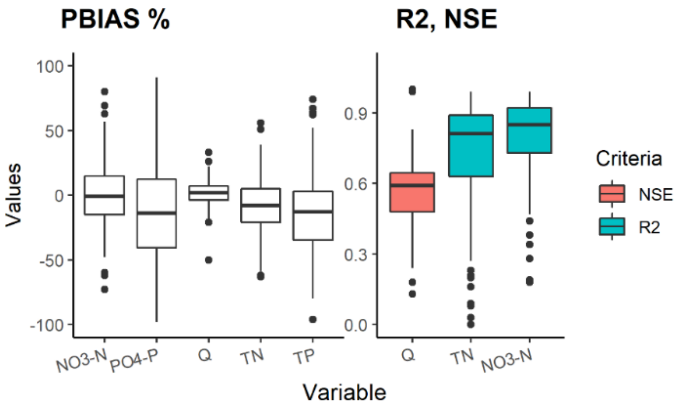

FIGURE 2. Model performance results for daily flows and monthly concentrations
Source: Plunge et al. (2022b).

In addition to the preparation of RBMPs (AAA, 2021), this system has already been used for the preparation of HELCOM periodic reports on pollution loads, which are used to assess the implementation of the BSAP and the compliance of member countries with the nutrient input ceilings (NIC) for the protection of the Baltic Sea (HELCOM, 2023a). The RMS is also applied for the national state of environment reporting (AAA, 2022), reporting emissions for the EEA (2024). This system was also used to fulfil various other EPA needs. For example, evaluating the potential of best management practices (BMPs) to reduce diffuse pollution from agriculture (Plunge, 2020), assessing the climate change impacts (Gudas & Plunge, 2021), to name a few.

It has also been applied in multiple scientific works. One study (Plunge et al., 2022b) has evaluated consequences of climate change on surface water bodies in Lithuania. Another one, utilizing the RMS, investigated how the effectiveness of BMPs changes with the advancement of climate warming (Plunge et al., 2022a). The costs of agricultural diffuse water pollution abatement to reach water protection goals for Lithuania with changing climate has also been evaluated and published in a scientific paper (Plunge et al., 2023a). In addition, the developed RMS was used to test various tools developed to support SWAT+ modelling efforts (Plunge et al., 2024; Plunge et al., 2023b).

There are also many initiatives and further work planned with this system. For example, a project "Integrated water management in Lithuania" funded within the EU LIFE program will run from 2024 to 2033 (European Commission [EC], 2024). Part of the project's activities is related to updating, improving and applying the RMS for Lithuania, as well as transferring it to selected river basins within the Nemunas river basin in Poland. Another LIFE project is currently underway in Latvia (LIFE GoodWater IP, 2020), which includes the transfer and application of the RMS for the Latvian territory among its activities. This project will continue until 2027.

This work with the RMS is not a unique attempt to apply the SWAT or SWAT+ model in Lithuania or neighboring countries. Different studies have employed this model in large scale applications in Lithuania (Čerkasova, 2019; Čerkasova et al., 2018, 2021, 2024), neighboring Poland (Kundzewicz et al., 2018; Marcinkowski et al., 2022), Estonia (Tamm et al., 2018) and Ukraine (Osypov et al., 2023; Kryshtop et al., 2024). However, there is an important distinction. The RMS is an ongoing project within a decision-making institution that aims to provide river basin modelling capabilities to water and agricultural management institutions. It is intended to be open-source and freely shared so that scientific institutions can benefit from this investment, as well as test and improve the system. Certainly, water management institutions in other countries have authoritative national-scale models, often supported by academic organizations or earth system modelling agencies (Arnold et al., 2020). However, to the best of our knowledge, this case is quite unique in the Central and Eastern European countries, where governmental agencies with very limited resources would embark to develop and manage such an advanced river basin modelling system.

There are multiple issues which have been noticed a decade ago when embarking on this challenge (Plunge, 2013). Several of them still persist, such as access to reliable data on pollution sources, attracting and retaining skilled specialists within national institutions, and adapting to new versions and revisions of SWAT. However, because this is an ongoing and integrated effort within the institutions, there are many ways to overcome these problems. This might not be the case for a short-term project focused on a single question, which might require a sophisticated model. Unfortunately, after such projects or thesis work is finished, the investment in developing these tools is often lost because the funding, specialists, or both are gone.

While the RMS has been relatively successful on the practical management level, it remains a challenge to meet the most pressing practical or policy needs. This is due to the variety of needs that cannot be addressed by the SWAT model without prior preparation and parameterization of specific scenarios. This is very time-consuming, and time and other resources may be scarce in critical situations. While SWAT is a versatile tool, it may be inappropriate for handling some types of mitigation measures realistically, e.g. channel and floodplain restoration. These limitations are hard to apprehend for policymakers, who do not have much knowledge about the efforts required for model adjustments and nuances. The effective and user-friendly operation of the RMS requires simpler and more accessible tools for data preparation, extraction and presentation in order to maintain its effectiveness and relevance for policy makers and the general public. This could serve as a potential direction for further development in the future.

Conclusions

Lithuania's river modelling system (RMS) has evolved from a test case for a valuable tool for water and agricultural management. Developed to help with European regulations, the RMS is now a part of environmental decision-making. Its integration of the SWAT model and extensive data sources enables comprehensive analysis and informed policy formulation. The RMS has demonstrated its reliability and effectiveness in various applications, including preparing management plans, compiling pollution reports, and supporting scientific research on climate change and effectiveness of pollution abatement measures. Ongoing initiatives such as the LIFE Integrated Water Management project underscore its continued relevance and potential for regional impact. Despite challenges such as data reliability and retention of skill within the institution, the RMS persists due to institutional commitment and collaborative efforts. Lithuania's experience with the RMS highlights the value of continuous investment in integrated modelling systems for sustainable environmental governance. Through collaboration and innovation, the RMS represents a paradigm shift towards more resilient and advanced water and agricultural management practices. Furthermore, the open-source nature of the developed modelling system presents the potential for it to be adopted by other countries creating more opportunities for cooperation.

Acknowledgments

This work was carried out within the LIFE22-IPE-LT-LIFE-SIP-Vanduo project (Integrated water management in Lithuania, ref: LIFE22-IPE-LT-LIFE-SIP-Vanduo/101104645, cinea.ec.europa.eu), funded by the European Union LIFE program under the grant agreement No 101104645. Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or European Climate, Infrastructure and Environment Executive Agency (CINEA). Neither the European Union nor the granting can be held responsible for them.

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Summary

From a test case to a trusted tool: Lithuania's evolving SWAT system for water and agricultural management. Lithuania's development of the river modelling system (RMS) exemplifies an institutional development and application of integrated modelling for water and agricultural management. What started as a test case, continued to develop focusing on environmental compliance with the EU regulations. Currently, the RMS is a part of decision-making. By incorporating the soil and water assessment tool (SWAT) model and comprehensive data sources, the system facilitates in-depth analysis and policy formulation. Applications in water management plans, pollution assessments, and climate change studies demonstrate the reliability of RMS. Despite data quality and skill retention challenges, institutional commitment and collaboration ensure the RMS's persistence. This experience emphasizes the value of sustained investment in integrated modelling systems for achieving sustainable environmental governance and signifies Lithuania's shift towards data driven green transition practices.